Shell evolution and shape coexistence in exotic nuclei

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Introduction

It is well known that nucleons are arranged in specific shells resulting in greater stability, analogous to the electron shells in the atom and that this shell structure was expected to be very robust in the whole nuclear chart. However, with new experimental techniques and progress in the production of radioactive ion beams during the last two decays, we are now aware that the shell structure changes when moving far away from stability. This so-called shell evolution is related to certain properties of the strong nuclear force, which affect the energies of proton and neutron orbitals when the neutron-to-proton ratio changes. Furthermore, the shape coexistence where particle-hole excitations over a major shell and quadrupole correlations are favoured due to inversion of orbitals and reduced shell gaps. In extreme cases proven in the lighter mass regions, new magic numbers appear and some other conventional ones disappear and intruder correlations change the ground state deformation, causing the phenomena called island of inversion. In the present manuscript, these aspects will be discussed in the ^{78}Ni region via neutron-rich Cu isotopes.

Neutron-rich Cu isotopes

Neutron-rich odd-mass Cu isotopes between N = 40 and N = 50, are excellent probes to study both single-particle and collective properties in the ^{78}Ni region. Mapping of their low-lying excited states will primarily help investigate the modifications of the proton single-particle states in the fp-shell ($1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$), and shed more light on shell evolution and its implications on deformation. Already earlier experimental and theoretical studies indicated that the low-lying states along the isotopic chain from ^{69}Cu to ^{79}Cu can be classified into three different types (although configurations can be mixed) [1–3]:

- the $3/2^-$ and $5/2^-$ "*single-particle*" states, dominated by the single-proton configurations, $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$, respectively,
- the "*particle-core coupled*" states from $9/2^-$ to $1/2^-$ and from $7/2^-$ to $1/2^-$ will appear as a result of the $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ single-particle excitations coupled to the first excited 2^+ state of the even-even Ni core, denoted as $2p_{3/2}\otimes 2^+_1$ and $1f_{5/2}\otimes 2^+_1$, respectively
- the $7/2^-$ "*intruder*" state arises from the excitation of a proton from the $1f_{7/2}$ orbital across the $Z = 28$ shell gap, leaving a hole in the $1f_{7/2}$ orbit, *i.e.* $\pi 1f^{-1}_{7/2}$.

Recent experiments performed at RIKEN radioactive beam facility using different methodologies will be presented.

The first experimental study aimed at studying proton-intruder states that are predicted to show prolate deformation as a result of particle-hole excitations across the Z=28 proton shell gap. Low-lying states in ^{75,77}Cu were investigated by the ^{76}Zn$(p, 2p)^{75}$Cu and ^{78}Zn$(p, 2p)^{77}$Cu knockout reactions at incident energies of 265 and 260 MeV/nucleon, respectively. The experiment was performed at the Radioactive Isotope Beam Factory,

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RIKEN under the SEASTAR experimental campaign. In-flight fission of a ^{238}U beam at 345 MeV/nucleon was induced by bombarding a 3-mm thick ^{9}Be target. The isotopes of interest, ^{76}Zn and ^{78}Zn, were selected in the BigRIPS fragment separator [6, 7] and impinged on the secondary 102(1) mm-thick liquid hydrogen (LH_2) target placed in the MINOS cylindrical time-projection chamber (TPC) [8]. The DALI2 NaI array [9] surrounded the MINOS device for the detection of the γ rays. The largest $\pi 1f^{-1}_{7/2}$ proton-hole strengths were deduced for the $7/2^{-}$ states at 1484 keV in ^{75}Cu and 2068 keV in ^{77}Cu. The work provided, for the first time, evidence for a parabolic behavior of the excitation energies of intruder states in the neutron-rich Cu isotopes as a function of the neutron number, suggesting a coexistence between spherical and moderately prolate shape for the ground and low-lying intruder states in ^{75,77}Cu[10, 11].

The second experimental work was performed to study the collective states in the ^{78}Ni region as a result of particle-core coupled excitations. The ^{77}Cu nucleus was the main scope of the experiment. Exotic secondary beam particles including ^{77}Cu were produced similar to the experiment described above, by induced fission of the ^{238}U beam on a 3 mm thick ^{9}Be target. The uranium beam was accelerated to an energy of 345 MeV/nucleon with an average beam intensity of 20 pnA. Fission products were selected and transported by the BigRIPS fragment separator. Coulomb excitation of the fragments was performed on a 900 mg/cm^2 thick ^{197}Au target, mounted in front of the Zero Degree Spectrometer (ZDS) [7]. The DALI2 NaI array was used to detect de-excitation gamma ray measured in coincidence with beam-like particles identified in the ZDS. The preliminary results on the ^{77}Cu nucleus and several different nuclei in the ^{78}Ni region will be presented during the oral presentation.

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